

# Fundamental physics and Lorentz violation

Ralf Lehnert

*CENTRA, Área Departamental de Física, Universidade do Algarve*  
*8000-117 Faro, Portugal*  
 rlehnert@ualg.pt

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## Abstract

The violation of Lorentz symmetry can arise in a variety of approaches to fundamental physics. For the description of the associated low-energy effects, a dynamical framework known as the Standard-Model Extension has been developed. This talk gives a brief review of the topic focusing on Lorentz violation through varying couplings.

## 1 Introduction

On the one hand, the Standard Model (SM) of particle physics is extremely successful phenomenologically. On the other hand, this conference is called *What Comes Beyond the Standard Model* because it is generally believed that the SM is really the low-energy limit of a more fundamental theory incorporating quantum gravity. Experimental research in this field faces various challenges. They include the expected Planck suppression of quantum-gravity signatures and the absence of a realistic underlying framework.

A promising approach for progress in quantum-gravity phenomenology is the identification of relations that satisfy three principal criteria: they must hold exactly in known physics, they are expected to be violated in candidate fundamental theories, and they must be testable with ultra-high precision. Spacetime symmetries satisfy all of these requirements. Lorentz and CPT invariance are key features of currently accepted fundamental physics laws, and they are amenable to Planck-sensitivity tests. Moreover, Lorentz and CPT breakdown has been suggested in a variety of approaches to fundamental physics. We mention low-energy emergent Lorentz symmetry [1],

strings [2], spacetime foam [3], nontrivial spacetime topology [4], loop quantum gravity [5], noncommutative geometry [6], and varying couplings [7]. The latter of these mechanism will be discussed in more detail in this talk.

At presently attainable energies, Lorentz and CPT violating effects are described by a general extension of the SM. The idea is to include into the SM Lagrangian Lorentz and CPT breaking operators of unrestricted dimensionality only constrained by coordinate independence [8]. This Standard-Model Extension (SME) has provided the basis for many investigations placing bounds on Lorentz and CPT violation. For the best constraints in the matter and photon sectors, see Ref. [9] and Refs. [10, 11], respectively. Note that certain Planck-suppressed SME operators for Lorentz and CPT breaking provide alternative explanations for the baryon asymmetry in our universe [12] and the observed neutrino oscillations [13].

## 2 Lorentz violation through varying couplings

Early speculations in the subject of varying couplings go back to Dirac's numerology [14]. Subsequent theoretical investigations have shown that time-dependent couplings arise naturally in many candidate fundamental theories [15]. Recent observational claims of a varying fine-structure parameter  $\alpha$  [16] have led to a renewed interest in the subject [17].

Varying couplings are associated with spacetime-symmetry violations. For instance, invariance under temporal and/or spatial translations is in general lost. Since translations are closely interwoven with the other spacetime transformations in the Poincaré group, one anticipates that Lorentz symmetry might be affected as well. This is best illustrated by an example. Consider the Lagrangian  $\mathcal{L}$  of a complex scalar  $\Phi$ , and suppose a spacetime-dependent parameter  $\xi(x)$  is coupled to the kinetic term:  $\mathcal{L} \supset \xi \partial_\mu \Phi \partial^\mu \Phi^*$ . An integration by parts yields  $\mathcal{L} \supset -\Phi (\partial_\mu \xi) \partial^\mu \Phi^*$ . If, for instance,  $\xi$  varies smoothly on cosmological scales,  $(\partial_\mu \xi) = k_\mu$  is essentially constant locally. The Lagrangian then contains a nondynamical fixed 4-vector  $k_\mu$  selecting a preferred direction in the local inertial frame violating Lorentz symmetry.

The above example can be generalized to other situations. For instance, non-scalar fields can play a role, and Lorentz violation can arise through coefficients like  $k_\mu$  in the equations of motion or in subsidiary conditions. Note that the Lorentz breaking is independent of the chosen reference frame: if  $k_\mu \neq 0$  in a particular set of local inertial coordinates,  $k_\mu$  is nontrivial in any coordinate system. In the next section, we show that varying couplings can arise through scalar fields acquiring expectations values in a cosmological

context. Note, however, that the above argument for Lorentz violation is independent of the mechanism driving the variation of the coupling.

### 3 Four-dimensional supergravity cosmology

Consider a Lagrangian  $\mathcal{L}_{\text{sg}}$  with two real scalars  $A$  and  $B$  and a vector  $F^{\mu\nu}$ :

$$\begin{aligned} \frac{4\mathcal{L}_{\text{sg}}}{\sqrt{g}} &= \frac{\partial_\mu A \partial^\mu A + \partial_\mu B \partial^\mu B}{B^2} - 2R - M F_{\mu\nu} F^{\mu\nu} - N F_{\mu\nu} \tilde{F}^{\mu\nu}, \\ M &= \frac{B(A^2 + B^2 + 1)}{(1 + A^2 + B^2)^2 - 4A^2}, \quad N = \frac{A(A^2 + B^2 - 1)}{(1 + A^2 + B^2)^2 - 4A^2}, \end{aligned} \quad (3.1)$$

where  $g^{\mu\nu}$  represents the graviton and  $g = -\det(g_{\mu\nu})$ , as usual. We have denoted the Ricci scalar by  $R$ , the dual tensor is  $\tilde{F}^{\mu\nu} = \varepsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}/2$ , and the gravitational coupling has been set to one. Then, the Lagrangian (3.1) fits into the framework of the pure  $N = 4$  supergravity in four spacetime dimensions.

To investigate Lagrangian (3.1) in a cosmological context, we assume a flat Friedmann-Robertson-Walker universe and model galaxies and other fermionic matter by including the energy-momentum tensor  $T^{\mu\nu}$  of dust, as usual.<sup>1</sup> In such a situation, the equations of motion can be integrated analytically [7] yielding a nontrivial dependence of  $A$  and  $B$  (and thus  $M$  and  $N$ ) on the comoving time  $t$ . Comparison with the usual electrodynamics Lagrangian in the presence of a  $\theta$  angle shows  $\alpha \equiv 1/4\pi M(t)$  and  $\theta \equiv 4\pi^2 N(t)$ , so that the fine-structure parameter and the  $\theta$  angle acquire related time dependences in our supergravity cosmology.

If mass-type terms  $\mathcal{L}_m = -\sqrt{g}(m_A A^2 + m_B B^2)/2$  for the scalars are included into Lagrangian (3.1), our simple model can match the observed late-time acceleration of the cosmological expansion [7]. Note also that the scalars themselves obey Lorentz-violating dispersion relations [7, 18].

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<sup>1</sup>The dust can be accommodated into the supergravity framework, which also contains fermions uncoupled from the scalars.

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